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The initiation and early tectonic significance of the Outer Hebrides Fault Zone, Scotland

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Abstract – The Outer Hebrides Fault Zone is a major ESE-dipping detachment exposed within basement gneisses of the Archaean–Palaeoproterozoic Lewisian Complex, northwest Scotland. The fault zone exhibits a long-lived displacement history and was active during Proterozoic, end-Silurian, Carboniferous and Mesozoic times. The earliest deformation event preserved onshore was associated with top-to-the-NW ductile thrusting. A previous study proposed that thrust-related protomylonitic and mylonitic fabrics are cross-cut by amphibolites ('Younger Basics') and Laxfordian granite and pegmatite sheets. This evidence was used to suggest that ductile thrusting occurred during the Palaeoproterozoic Inverian event at *c.* 2500 Ma. Our observations demonstrate, however, that mylonitic fabrics within the ductile thrust zone are superimposed on *all* components of the gneiss complex including amphibolites and Laxfordian intrusions. It therefore follows that the Outer Hebrides Fault Zone cannot be older than *c.* 1685 Ma, the age of recently dated Laxfordian granites in the Outer Hebrides. Geochronological studies have shown that the basement blocks of the northern Outer Hebrides and Scottish mainland have different geological histories and were amalgamated during Proterozoic times at or after *c*. 1700 Ma. We propose that early ductile thrusting along the Outer Hebrides Fault Zone formed part of this amalgamation process leading to burial and reheating of the footwall gneisses in Lewis and north Harris. This would account for the *c*. 1100 Ma thermal event recorded by previous workers and implies that ductile thrusting along the Outer Hebrides Fault Zone is of Grenvillian age.

Keywords: Outer Hebrides, fault zones, Laxfordian, Grenville, reactivation, thrust faults.

1. Introduction

The Outer Hebrides Fault Zone is a major, ESE-dipping detachment exposed within basement gneisses of the Archaean–Palaeoproterozoic Lewisian Complex of the Outer Hebridean islands (Fig. 1; Jehu & Craig, 1925, 1926, 1927, 1934; R. H. Sibson, unpub. Ph.D. thesis, Univ. London, 1977; Sibson, 1977; Lailey, Stein & Reston, 1989; Fettes *et al.* 1992; Butler, Holdsworth & Strachan, 1995; MacInnes, Alsop & Oliver, 2000; Imber *et al*. 1997, 2001; Osinski, Alsop & Oliver, 2001). The trace of the Outer Hebrides Fault Zone runs nearly parallel to the Moine Thrust, the western margin of the Caledonian orogenic belt, which crops out *c.* 85 km to the east on the Scottish mainland (Fig. 1a). Seismic reflection profiles suggest that the Outer Hebrides Fault Zone dips consistently at *c.* 25° E to SE down into the lower crust, intersecting and possibly offsetting the Moho at *c.* 25 km depth (Smythe *et al*. 1982; Peddy, 1984). Interpretations of offshore borehole and seismic reflection data suggest that the fault zone was active during Proterozoic, Carboniferous and Mesozoic extension (e.g. Stein, 1988, 1992). The exceptional onshore exposure of the Outer Hebrides Fault Zone probably results from uplift in the footwall of the Permo-Triassic Minch Fault (Fig. 1b), combined with the effects of later regional uplift related to underplating of basalts below this part of northwest Scotland during the opening of the North Atlantic (Brodie & White, 1994; Roberts & Holdsworth, 1999).

On the basis of systematic, along-strike variations in fault rock distribution, the onshore expression of the Outer Hebrides Fault Zone can be divided into two distinct segments separated by the NW–SE-trending South Harris Shear Zones (Fig. 1b; Butler, Holdsworth & Strachan, 1995; Imber *et al.* 2001). Overprinting relationships between different fault rocks and structures exposed along the northern segment preserve evidence for at least five *major* fault-related deformation events. Starting with the oldest event, these are: (1) top-to-the-NW thrusting in a broad (< 6 km thick) mylonitic shear zone; (2) brittle top-to-the-W thrusting producing widespread cataclasite and pseudotachylyte; (3) sinistral top-to-the-NE strike-slip in a network of macroscopically ductile phyllonitic shear zones; (4) brittle–ductile top-to-the-SE extension focused within and along the margins of the phyllonitic shear zone network; and (5) brittle top-to-the-E extension along steeply dipping normal faults. In contrast, four major movement events have

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been recognized along the southern segment of the Outer Hebrides Fault Zone (Butler, Holdsworth & Strachan, 1995; Imber *et al*. 2001). Starting with the oldest, these are: (1) brittle top-to-the-W thrusting producing widespread cataclasite and pseudotachylyte; (2) sinistral top-to-the-NE strike-slip in a network of macroscopically ductile phyllonitic shear zones; (3) brittle–ductile top-to-the-E extension focused within and along the margins of the pre-existing phyllonite belts; and (4) brittle top-to-the-E and -ENE slip along steep to moderately dipping faults. Events 2, 3, 4 and 5 along the northern segment have been correlated with events 1, 2, 3 and 4 in the southern Outer Hebrides on the basis of similarities in kinematic history and fault rock textures (Butler, Holdsworth & Strachan, 1995; Imber *et al*. 2001). This correlation of deformation events is similar to that suggested in the seminal study of R. H. Sibson (unpub. Ph.D. thesis, Univ. London, 1977), although he did not recognize the sinistral displacements. Offshore interpretation of geophysical data (Stein, 1992) and onshore interpretation of depositional patterns in the Torridonian (e.g. Williams, 2001) suggest that an additional, regionally significant normal faulting event occurred along the Minch Fault/Outer Hebrides Fault Zone synchronous with the deposition of the Torridon Group sandstones in northwest Scotland *c*. 1000 Ma (see also Stewart, 2002). There is no unequivocal evidence onshore for this fault movement (but see Section 3.c). The presence of presumably undeformed and unmetamorphosed Torridonian rocks in the immediate hanging wall of the Outer Hebrides Fault Zone beneath the Minch and Sea of the Hebrides basins implies that the 6 km thick, thrust-related greenschist- to amphibolite-facies mylonitic shear zone (event 1, northern fault segment) formed prior to 1000 Ma. Although previous workers have described *local* occurrences of mylonite on Barra and South Uist whose kinematics are consistent with top-to-the-NW shear (MacInnes, Alsop & Oliver, 2000; Osinski, Alsop & Oliver, 2001), the absence of a major ductile shear zone leads us to concur with Butler, Holdsworth & Strachan (1995) who suggest that there is no evidence for *regional*, top-to-the-NW ductile thrusting along the southern segment of the Outer Hebrides Fault Zone (Fig. 1b).

In this contribution, we describe critical field relationships on the island of Scalpay (Fig. 1b, c) that constrain the timing of the ductile thrusting along the northern segment, and hence the age of Outer Hebrides Fault Zone initiation, to being post-*c.* 1700 Ma. Our interpretation contrasts with that of previous workers who proposed a much older, Inverian age (*c.* 2500 Ma) for fault initiation in the Outer Hebrides (Lailey, Stein & Reston, 1989). Finally, we place our findings in a regional context in the light of published geochronological studies of the Lewisian Complex in the Outer Hebrides and elsewhere (Cliff & Rex, 1989; Cliff, Rex & Guise, 1998; Friend & Kinny, 2001).

2. Field relationships on Scalpay

The island of Scalpay provides a well-exposed NW to SE section from the Lewisian Complex basement gneisses of 'foreland' up into an overprinting shear zone with SE-dipping protomylonitic to mylonitic fabrics (Fig. 1b, c; R. H. Sibson, unpub. Ph.D. thesis, Univ. London, 1977). The belt of mylonitic fabrics here is at least 1000 m thick and its upper boundary is not exposed. Scalpay is somewhat anomalous in that brittle fault rocks formed during later top-to-the-W Caledonian thrusting are less widely developed compared to other parts of the northern fault zone segment (e.g. R. H. Sibson, unpub. Ph.D. thesis, Univ. London, 1977; J. Walker, unpub. Ph.D. thesis, Univ. London, 1990; Fettes *et al.* 1992; C. A. Butler, unpub. Ph.D. thesis, Univ. Durham, 1995; J. Imber, unpub. Ph.D. thesis, Univ. Durham, 1998). However, the cross-cutting relationships displayed by ductile, top-to-the-NW thrust-related fabrics and minor intrusions within Lewisian gneisses are critical to determining the relative age of the earliest mylonitic fabrics in the northern segment of the Outer Hebrides Fault Zone.

2.a. Lithologies, macrostructure and deformation environment

Four main lithological/structural associations are preserved on Scalpay: (1) the Lewisian protolith assemblage of orthogneisses which crop out in the northwest of the island; (2) a zone of these gneisses in southeastern Scalpay that are overprinted by a SE-dipping protomylonitic and mylonitic fabric; (3) infrequent, Caledonian-age top-to-the-W thrust-related cataclasite and pseudotachylyte veins that cross-cut both the mylonitic fabric and Laxfordian-age pegmatite sheets in the 'foreland'; and (4) discrete, NE–SW-trending Caledonian sinistral strike-slip (top-to-the-NE) phyllonite belts that lie concordant to and locally rework the mylonitic fabrics at Cnoc na Croich, Kennavay and elsewhere in southeastern Scalpay (Fig. 1c). The nature and tectonic significance of these Caledonian-age phyllonitic shear zones have been discussed in detail elsewhere (Butler, Holdsworth & Strachan, 1995; Imber *et al.* 1997; Imber *et al.* 2001) and they are not considered further here.

The protolith assemblage in Scalpay consists of hornblendic acid orthogneisses, with infrequent basic–ultrabasic bodies up to several hundred metres in diameter (the 'Older Basics' of Fettes *et al.* 1992), and later locally discordant amphibolite sheets (the 'Younger Basics' of Fettes & Mendum, 1987), all of which are cross-cut by granitic pegmatite sheets and veins. The Younger Basics have been correlated with the Scourie dykes that intrude the Lewisian Complex on the Scottish mainland and have been dated there at 2400–2000 Ma (U–Pb baddelyite: Heaman & Tarney, 1989). The Scourie dykes are themselves part of a major Proterozoic dyke swarm that extends from

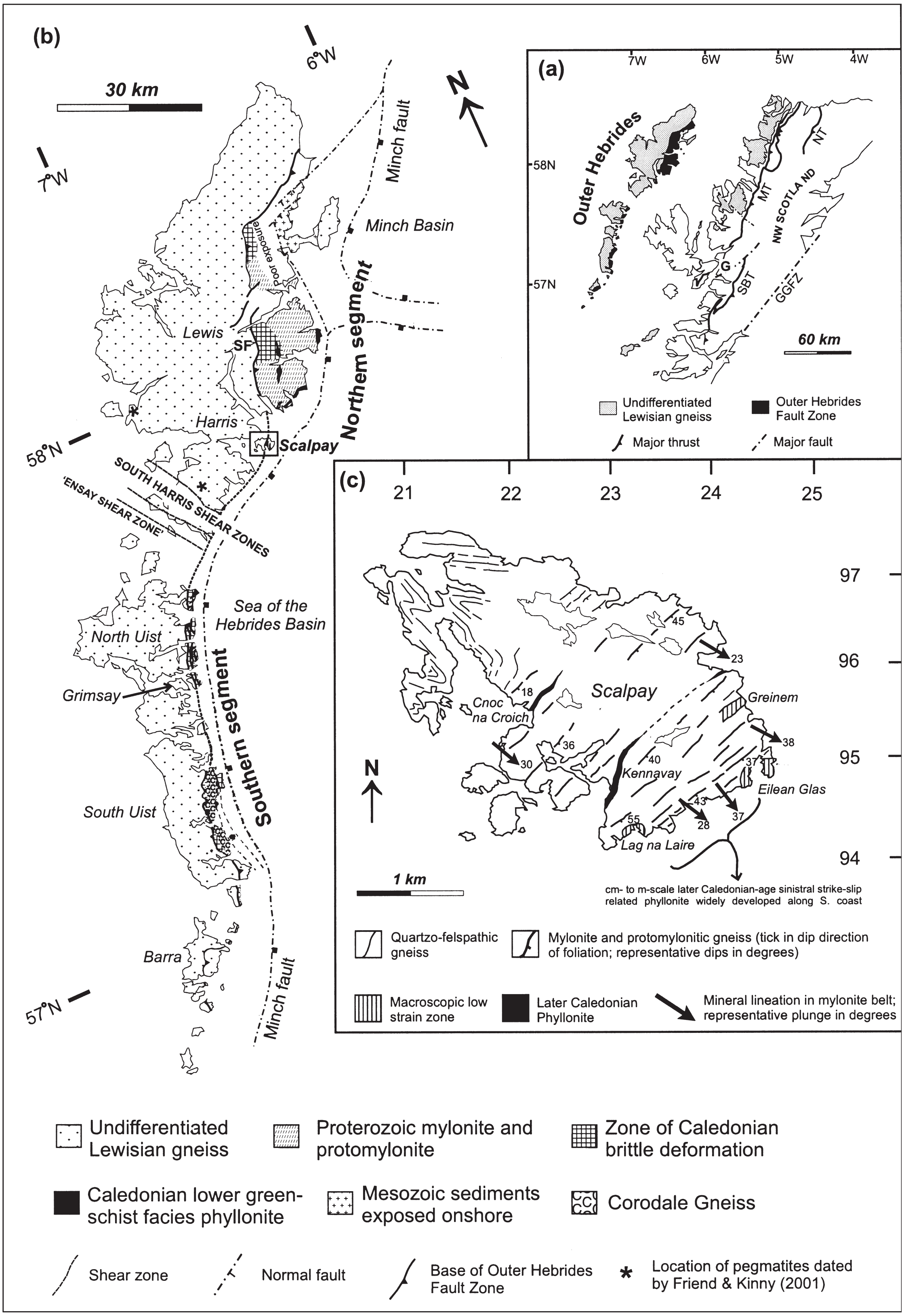

Figure 1. (a) The Outer Hebrides Fault Zone in relation to major Caledonian structures exposed on the Scottish mainland. MT – Moine Thrust; NT – Naver Thrust; SBT – Sgurr Beag Thrust; GGFZ – Great Glen Fault Zone; G – Glenelg. (b) Simplified geological map showing the general distribution of fault rocks within the Outer Hebrides Fault Zone, major offshore basins and the main basin-bounding faults. Map is compiled from R. H. Sibson (unpub. Ph.D. thesis, Univ. London, 1977), Fettes *et al.* (1992), C. A. Butler (unpub. Ph.D. thesis, Univ. Durham, 1995) and J. Imber (unpub. Ph.D. thesis, Univ. Durham, 1998). SF – Seaforth Head. Box shows location of map shown in Figure 1c. (c) Simplified geological map of the Outer Hebrides Fault Zone showing the fault rock distribution on Scalpay. Map is complied from J. Walker (unpub. Ph.D. thesis, Univ. London, 1990), C. A. Butler (unpub. Ph.D. thesis, Univ. Durham, 1995) and J. Imber (unpub. Ph.D. thesis, Univ. Durham, 1998).

Scandinavia, through Scotland and Greenland to Baffin Island (Escher, Jack & Watterson, 1976). The granitic pegmatite veins in the Outer Hebrides are widespread and have been attributed to mainly Laxfordian tectonothermal activity at 1700 Ma (Fettes & Mendum, 1987). SHRIMP™ analyses of zircon grains from two granite sheets in western Lewis yielded mean ages of 1674 ± 3 and 1683 ± 9 Ma (Friend & Kinny, 2001; Fig. 1b). The significance of these isotopic ages in constraining the relative age of fault initiation is discussed in Sections 2.b and 3.

The lower margin of the mylonitic zone is gradational and characterized by a progressive change in the orientation of the compositional banding in the gneisses from a mainly NW–SE trend in the foreland to a NE–SW trend within the mylonitic zone (Fig. 1c). The mylonitic zone itself is heterogeneous and comprises interbanded packages of quartzofeldspathic and phyllosilicate-bearing protomylonitic to mylonitic gneiss, together with highly deformed, concordant sheets of mylonitic amphibolite and pegmatite (Imber *et al.* 2001). Qualitatively, the proportion of mylonitic to protomylonitic gneiss appears to increase towards the south and east. R. H. Sibson (unpub. Ph.D. thesis, Univ. London, 1977) has suggested that this fabric distribution reflects a general increase in strain towards the southeast and away from the lower margin of the mylonite belt. Within packages of the quartzofeldspathic protomylonitic–mylonitic gneiss, the SE-dipping foliation is associated with a consistently SE-plunging mineral stretching lineation (Fig. 1c) defined principally by partially recrystallized 'ribbon' quartz grains. Kinematic indicators, including asymmetric shear bands and σ-type quartz and feldspar porphyroclasts, are everywhere consistent with top-to-the-NW shear (that is, thrusting) across the mylonitic belt. Within most of the packages of phyllosilicate-bearing mylonitic gneiss, the SE-dipping foliation also carries a generally SE-plunging lineation defined by syn-tectonic quartz–actinolite or quartz–chlorite fibres. Asymmetric chlorite-rich shear bands and quartz and feldspar porphyroclasts define a top-to-the-NW sense of thrusting.

Collectively, the thrust-related protomylonitic to mylonitic gneisses consist mainly of flattened, partially altered feldspar (oligoclase and K-feldspar) grains, hornblende porphyroclasts, quartz ribbons, infrequent biotite laths and syn-tectonic aggregates of sericite, albite, fibrous actinolite and epidote. The quartz ribbons display strong undulose extinction and locally well-developed core-and-mantle microstructures. Actinolite fibres, which are typically oriented sub-parallel to the macroscopic mineral stretching lineation, fill the intra- and trans-granular extension fractures that are commonly observed to cross-cut individual hornblende grains and deformed amphibolite sheets (e.g. Fig. 2). The co-existence of hornblende and biotite (present in the parent gneisses) with syn-tectonic actinolite, and the development of quartz core-and-mantle structures and ribbons, suggest that ductile, top-to-the-NW thrusting occurred under upper greenschist to lower amphibolite facies conditions, that is, temperatures in excess of 500 °C (Miyashiro, 1994; Passchier & Trouw, 1996). This is consistent, within error, with estimates of 535 ± 50 °C (Fettes & Mendum, 1987) and 520 ± 60 °C (White, 1996) obtained from the Outer Hebrides Fault Zone mylonitic zone further north at Seaforth Head (Fig. 1b). We conclude, therefore, that the mylonitic gneisses exposed on Scalpay formed within the mid-crust during top-to-the-NW overthrusting.

2.b. Cross-cutting relationships

On Scalpay, the orientation of intrusive phases relative to the mylonitic fabric is a useful qualitative strain marker (R. H. Sibson, unpub. Ph.D. thesis, Univ. London, 1977). Three elongate (> 200 m long) macroscopic low strain zones, in which sheets of Younger Basic amphibolite and Laxfordian granitic pegmatite are generally discordant to the mylonitic fabric, occur along the south and east coasts of the island (Lag na Laire, NG 232942; Eilean Glas, NG 245946; and Greinem, NG 245955; Fig. 1c). The dominant fabric in the orthogneisses is protomylonitic, but the planar and linear components are similarly oriented to those elsewhere in the mylonitic shear zone. A series of apparently discordant, folded Younger Basic sheets (mostly < 0.5 m thick) occur within the Lag na Laire low strain zone. As first recognized by R. H. Sibson (unpub. Ph.D. thesis, Univ. London, 1977), the margins of these amphibolite sheets are invariably oblique to the mylonitic foliation (Figs 2, 3a). This led Lailey, Stein & Reston (1989) to suggest that the igneous precursors of the amphibolite sheets were intruded *after* the earliest stages of mylonitization. The same authors also believed that the Laxfordian granitic pegmatites cross-cut and therefore post-dated the earliest mylonitic fabrics preserved in the low strain augen. On this basis, Lailey, Stein & Reston (1989) argued that the initiation of ductile, top-to-the-NW thrusting predated the intrusion of basic dykes at *c.* 2400 Ma, and probably occurred during the Inverian event that is dated on the Scottish mainland at *c.* 2500 Ma (Park *et al.* 1994).

We have re-examined the critical outcrops at Lag na Laire and propose an alternative interpretation to that of Lailey, Stein & Reston (1989). There are three critical lines of evidence demonstrating that all mylonitization post-dates basic dyke and granitic pegmatite emplacement. These are as follows:

(1) The protomylonitic fabric clearly passes without deflection from the orthogneisses into the thinner amphibolite sheets (Figs 2, 3b) within which it is defined by laterally discontinuous strands of sericite that wrap relatively undeformed, unaltered horn-

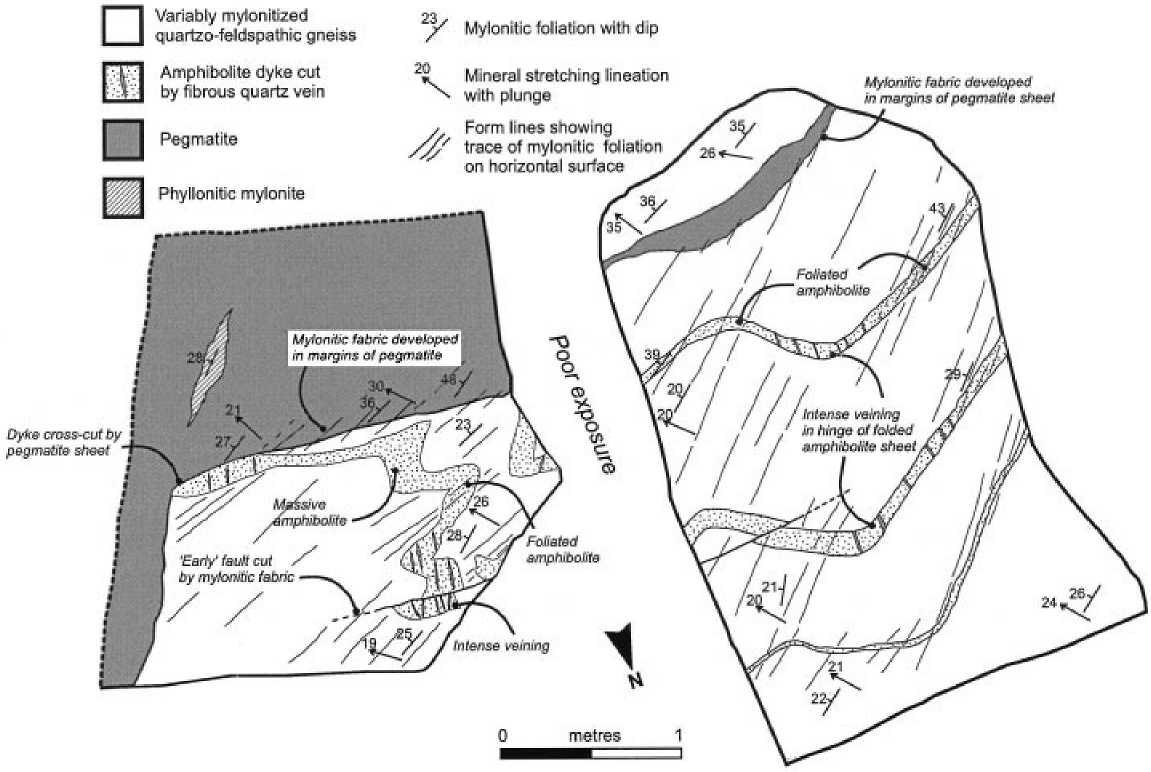

Figure 2. Sketch map showing typical overprinting relationships in horizontal exposure surfaces, Lag na Laire, Scalpay (Fig. 3a; Map reference: NG 232 942). Note the position of north to allow comparison with Figure 3a which shows the eastern (left hand) part of the outcrop.

blende and highly altered feldspar porphyroclasts (Fig. 3c). Although the cores of the thicker amphibolite sheets are massive and apparently undeformed, the protomylonitic fabric clearly passes into their margins.

(2) The amphibolites are cut by arrays of intra- and trans-granular extension fractures. These are infilled by aggregates of fibrous quartz and actinolite that are aligned parallel to the macroscopic mineral lineation. Macroscopic arrays of NE–SW-trending, fibrous quartz–epidote veins also cross-cut the thickest amphibolite sheets (Fig. 2). The orientation of the fibrous infills is generally consistent with tensile vein opening in a direction parallel to the thrust-related, SE-plunging mineral lineation. These veins are progressively sheared into concordance with the mylonitic foliation as they are traced from the more competent amphibolites into adjacent, less competent mylonitic quartzofeldspathic rocks (e.g. Imber *et al.* 2001, fig. 11d).

(3) The protomylonitic fabric is present in all pegmatites where it is developed to variable degrees. As is the case with the amphibolites, the thinnest pegmatites carry a through-going fabric, whereas the thickest examples are mainly massive and only foliated along their margins (Fig. 2). The microstructures of quartz and feldspar are identical to those observed in the host protomylonitic gneisses (see C. A. Butler, unpub. Ph.D. thesis, Univ. Durham, 1995). Top-to-the-NW shear band fabrics are widely preserved (Fig. 3d).

To summarize, our study shows that the thrust-related protomylonitic fabric in southeast Scalpay is *everywhere* superimposed on, and therefore post-dates, all components of the gneiss complex, including the Younger Basic amphibolites and the Laxfordian pegmatites. Similar relationships are preserved in the Seaforth Head area (Fig. 1b; C. A. Butler, unpub. Ph.D. thesis, Univ. Durham, 1995; J. Imber, unpub. Ph.D. thesis, Univ. Durham, 1998). In the following section, we discuss the timing and early tectonic significance of the mid-crustal ductile thrusting event in the light of published geological and geochronological studies in the Outer Hebrides and elsewhere.

3. Discussion

Recent geochronological studies by Friend & Kinny (2001) suggest that the steeply dipping, NW–SE-trending South Harris Shear Zones (Fig. 1b) are a major terrane boundary within the Lewisian Complex of the Outer Hebrides, juxtaposing Archaean gneisses in Lewis and north Harris (their Tarbert terrane) against a juvenile, Proterozoic arc complex in south Harris (their Roineabhal terrane) (Fig. 4). Friend & Kinny (2001) argued that terrane accretion occurred after *c.* 1675 Ma on the basis that Laxfordian-age granite sheets do not crop out in south Harris. In addition, they suggest that a further tectonic boundary (Ensay Shear Zone), separating the Roineabhal

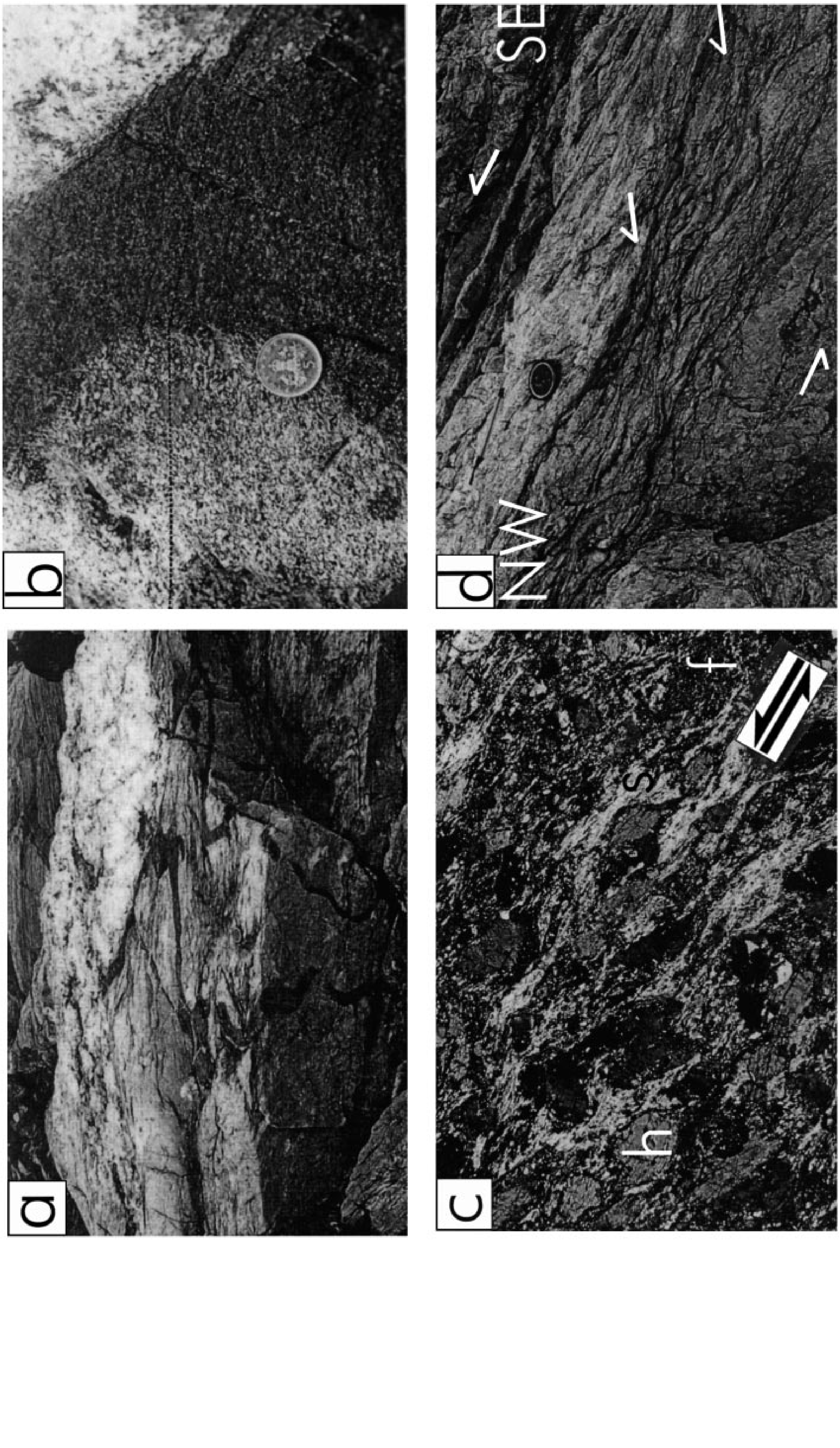

Figure 3. For legend see facing page.

terrane from the 'Uist block' to the south, is exposed on the island of Ensay (Figs 1b, 4). Transpressive convergence across the South Harris Shear Zones during accretion was probably responsible for the development of some or all of the earlier amphibolite- to locally granulite-facies shear zone fabrics documented widely in this region (see Fig. 4; e.g. Coward, 1984). A key question is, therefore, when did ductile thrusting occur along the Outer Hebrides Fault Zone relative to displacements in the vicinity of the South Harris Shear Zones? Two 'end-member' models are discussed below: (1) thrusting prior to terrane accretion, and (2) thrusting after terrane accretion. In this discussion, it is assumed that the Uist block was accreted at essentially the same time as the Roineabhal terrane.

3.a. Thrusting prior to terrane accretion

Friend & Kinny's (2001) data indicate there was a period of ≥ *c.* 10 Myr between the onset of Laxfordian granite sheet emplacement in Lewis (*c.* 1685 Ma) and terrane accretion (post *c.* 1675 Ma) in south Harris. Fettes *et al.* (1992) observed that many Laxfordian granite sheets which crop out to the west of the Outer Hebrides Fault Zone in south Lewis and north Harris exhibit a top-to-the-NW thrust-related solid-state deformational fabric of variable intensity. Fettes *et al.* (1992) suggested that deformation occurred during the later stages of intrusion emplacement and equated the thrusting to the earliest movements recognized along the Outer Hebrides Fault Zone. If correct, the intiation of the Outer Hebrides Fault Zone could therefore be Laxfordian and be restricted to the Tarbert terrane (Fig. 4a i) as it pre-dates accretion across the South Harris Shear Zones (Fig. 4a ii). We are, however, cautious about accepting this interpretation for two reasons. Firstly, no *systematic* structural study of the emplacement history of the Laxfordian granite and pegmatite sheets in the Outer Hebrides has yet been undertaken. The structures described could certainly be associated with emplacement of the igneous bodies during the late Laxfordian, but there is no compelling evidence linking these features to movements along the Outer Hebrides Fault Zone. Secondly, as Fettes *et al.* (1992) acknowledge, similar features have been noted in the Laxford Bridge/Scourie area on the Scottish mainland, where Peach *et al.* (1907) recorded occurrences of partially mylonitic granite or pegmatite in Lewisian gneisses apparently unaffected by shearing. Granite sheets in this part of the mainland basement have yielded U–Pb (SHRIMP™) zircon ages of *c.* 1855 Ma, and are therefore much older than, and unrelated to, those on the Outer Hebrides (Friend & Kinny, 2001). Late granite sheets of quite different ages within the Lewisian basement therefore carry similar syn-emplacement deformation features that cannot be tied or correlated into any single structural event. Thus, although we cannot rule out fault initiation synchronous with granite sheet emplacement *c.* 1685 Ma (Fig. 4a i–iv), our preferred solution (Fig. 4b; Section 3.b) suggests that the *main* phase of ductile thrusting for which evidence is preserved along the Outer Hebrides Fault Zone is likely to be significantly younger.

3.b. Thrusting after terrane accretion

If the main phase of thrusting occurred after terrane accretion in the vicinity of the South Harris Shear Zones (Fig. 4b i), it follows that the ductile thrust-related mylonites of the Outer Hebrides Fault Zone are generally younger than *c.* 1675 Ma. Their lower age limit is constrained by the presence of unmetamorphosed Torridonian strata (deposited *c.* 1000 Ma) in the fault zone hanging wall at depth offshore (e.g. Stein, 1992) and by cross-cutting pseudotachylyte veins that have been correlated with similar features in the southern Outer Hebrides and dated there at *c.* 430 Ma (Kelley, Reddy & Maddock, 1994).

Cliff & Rex (1989) showed that there is an abrupt transition in Rb–Sr biotite ages across the Langavat shear zone (the northern strand of the South Harris Shear Zones). Ages greater than 1300 Ma were obtained from gneisses to the south of the Langavat shear zone, whilst 'Grenvillian' ages (*c.* 1100 Ma) were obtained from texturally equilibrated, amphibolite-facies gneisses in Lewis and north Harris. Cliff & Rex (1989) attributed this age distribution to a 'general reheating' of the gneisses in the northern Outer Hebrides, followed by cooling due to postulated kilometre-scale, north-side-up displacements across the Langavat shear zone at *c.* 1100 Ma. The origins of this reheating event are not discussed by these authors. We suggest that, in the absence of any contemporaneous

Figure 3. Key field and thin section relationships from the mylonitic fault rocks of Scalpay. (a) General southwards view of foliated quartzofeldspathic gneiss (mid-grey), folded dark coloured amphibolite sheets ('Younger Basics') and large cross-cutting Laxfordian granitic pegmatite (lighter rock near top of picture), Lag na Laire low strain zone, Scalpay (Map reference: NG 232 942). Note that the protomylonitic fabric is in an axial planar orientation relative to the folds. This outcrop forms the eastern half of the map in Figure 2. (b) Close-up view of folded amphibolite sheet (dark rock) in the Lag na Laire exposure showing that the protomylonitic fabric (dashed line) overprints both the quartzofeldspathic gneisses (pale rocks) and the amphibolite. Note slight refraction of the foliation as it passes into the more competent Younger Basic sheet. (c) Thin section of protomylonitic fabric in amphibolite, with hornblende (h) and highly altered plagioclase porphyroclasts (f) wrapped by laterally discontinuous fine-grained sericite (s, pale speckled) and dark fibrous amphibole. Split arrows parallel to the macroscopic mineral lineation, top-to-the-NW shear. Field of view 6 × 3.7 mm, crossed polars. (d) Deformed Laxfordian pegmatite with top-to-the-NW S–C fabrics. From the margins of the Lag na Laire low strain zone, Scalpay (Map reference: NG 231 942).

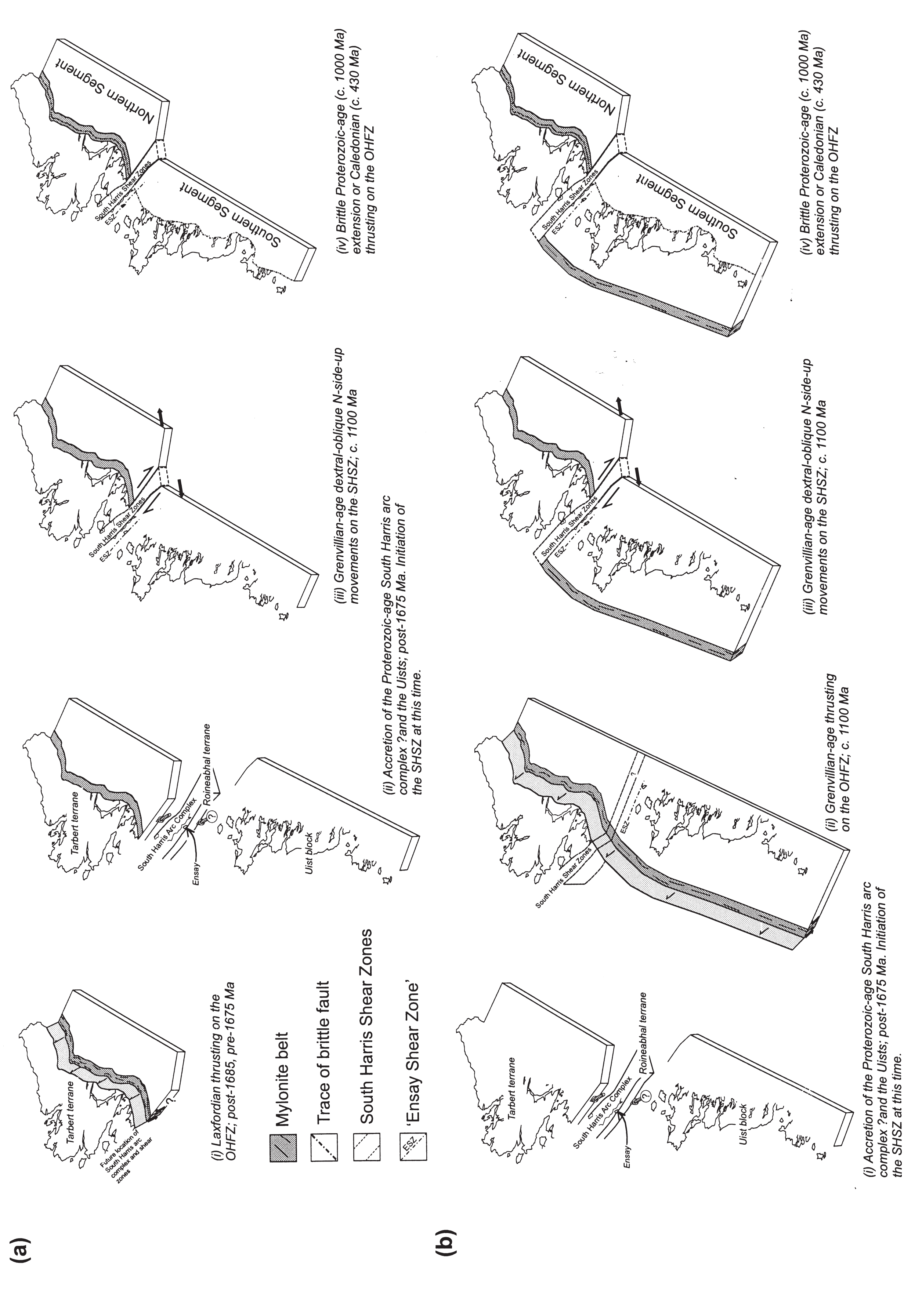

Figure 4. For legend see facing page.

igneous activity, the 'reheating' could reflect tectonic burial of the footwall gneisses around 1100 Ma due to ductile thrusting along the Outer Hebrides Fault Zone (Fig. 4b ii). Significantly, the temperatures attained during thrusting (*c.* 500 °C; Section 2.a) would have been sufficient to reset Rb–Sr biotite ages in the footwall gneisses (the biotite closure temperature for the Rb–Sr system is *c.* 320 °C: Ghent, Stout & Parrish, 1988), but are unlikely to have been high enough to fully reset the equivalent hornblende geochronometers (the hornblende closure temperature to argon is *c.* 530 ± 40 °C: Ghent, Stout & Parrish, 1988). This interpretation is, therefore, consistent with the predominantly Laxfordian ^{39}Ar–^{40}Ar hornblende ages (1600–1700 Ma) obtained from gneisses throughout Lewis and north Harris (Cliff, Rex & Guise, 1998).

Structural and kinematic studies of the South Harris Shear Zones (Graham, 1980; Coward & Park, 1987; C. A. Butler, unpub. Ph.D. thesis, Univ. Durham, 1995; T. Lapworth, unpub. Ph.D. thesis, Univ. Liverpool, 2001) have identified a 'late', greenschist-facies dextral–oblique slip event that uplifted Lewis and north Harris relative to south Harris. Assuming kilometre-scale displacements, the dextral–oblique slip event across the South Harris Shear Zones is consistent with the north-side-up event postulated by Cliff & Rex (1989) and it further suggests that any continuation of the Outer Hebrides Fault Zone ductile thrust mylonitic belt to the south of the South Harris Shear Zones would have been displaced towards the west so that it presently lies offshore (Fig. 4b iii).

3.c. Other regional implications

Our findings raise questions about fault movement events in different parts of the Outer Hebrides Fault Zone in both onshore and offshore regions, and may also shed new light on the relationship between the rocks of the Lewisian Complex on the Scottish mainland and those of the Outer Hebrides. The tectonic models discussed here imply that the southern segment of the Outer Hebrides Fault Zone is significantly younger than the thrust-related mylonite belt to the north (Fig. 4a iv, b iv). Cross-cutting relationships on the Uists and Barra show that brittle faults and pseudotachylyte/cataclasite veins are the oldest structures to crop out along the length of the southern segment. Although Kelley, Reddy & Maddock (1994) have dated a single pseudotachylyte thrust vein from the island of Grimsay (Fig. 1b) to *c.* 430 Ma, we cannot discount the possibility that some of the pseudotachylyte is older and perhaps related to the Proterozoic-age (*c.* 1000 Ma) extension event observed offshore (Stein, 1992; Imber *et al.* 2001). Osinski, Alsop & Oliver (2001) have pointed out that extension-related pseudotachylyte veins are widely developed within the Outer Hebrides Fault Zone on South Uist; this may also be true in other parts of the Outer Hebrides Fault Zone. We believe there is scope for a systematic ^{39}Ar–^{40}Ar study of pseudotachylyte fault veins (following techniques described by Kelley, Reddy & Maddock, 1994) to constrain further the timing of brittle deformation.

Friend & Kinny (2001) showed that there are major similarities between the basement of east Greenland and the Outer Hebrides, but that there is no clear correlation between the latter and the Lewisian basement of the Scottish mainland. These authors proposed that initial amalgamation of the Outer Hebrides and the Scottish mainland blocks is most likely to have occurred either along the Minch Fault (Fig. 1b), a steeply dipping normal fault that, on seismic sections, is seen to branch upwards from the Outer Hebrides Fault Zone (Stein, 1988, 1992), or along the Outer Hebrides Fault Zone itself. Although we cannot quantify the ductile thrust offsets *c.* 1100 Ma, the intensity of mid-crustal deformation and *c.* 6 km thickness of the mylonitic belt implies regionally significant displacements. This suggests that final amalgamation of the mainland and Outer Hebridean portions of the Lewisian complex was facilitated by the initiation of the Outer Hebrides Fault Zone. Our model implies that the gneisses in the Uists were carried in the hanging wall of the ductile thrust-related mylonitic belt (Fig. 4b ii). Thus they are likely to have experienced a different thermal history to the basement rocks in Lewis and north Harris. However, any attempt at correlating events in the basement gneisses of the Uists with those of the mainland will be complicated by the effects of later reactivations along the Outer Hebrides Fault Zone (e.g. see Imber *et al.* 2001) including up to 90 km of late Caledonian-age sinistral strike-slip displacement (Piper, 1992; Butler, Holdsworth & Strachan, 1995). We suggest that SHRIMP™ analyses of zircons from the Uists, coupled with Rb–Sr dating of syn-tectonic white mica (sericite) grains in the ductile mylonitic belt of the Outer Hebrides Fault Zone and later greenschist-facies fault rocks of the South Harris Shear Zones (cf. Freeman *et al.* 1997), would help clarify the timing and sequence of events involved in the final tectonic assembly of the Lewisian complex in northwest Scotland.

Our model proposing final amalgamation of the Lewisian Complex at *c.* 1100 Ma coincides in timing with Grenvillian collisional orogenesis in northeastern Canada (e.g. Rivers, 1997), Scandinavia (e.g. Brewer

Figure 4. Cartoons showing the two 'end-member' models for the possible timing of ductile thrusting along the Outer Hebrides Fault Zone (OHFZ) relative to displacements along the South Harris Shear Zones (SHSZ). (a) Thrusting prior to terrane accretion in south Harris and (b) Grenvillian thrusting subsequent to terrane accretion in south Harris. The geometry of the ductile thrust mylonitic belt is based on the present-day geometry of the Outer Hebrides Fault Zone and is, therefore, conjectural.

et al. 2002) and northwestern Ireland (Menuge & Daly, 1994). This implies that Grenvillian events played a significant role in the late Proterozoic evolution of some parts of the Scottish Highlands. These events may also be linked in some way to the formation of eclogite and its exhumation at *c.* 1050 Ma in Lewisianoid rocks preserved in the Moine Nappe at Glenelg on the Scottish mainland (Sanders, van Calsteren & Hawkesworth, 1984; Fig. 1a).

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